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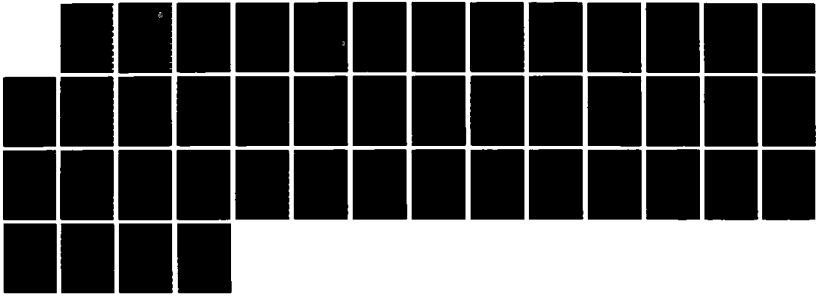

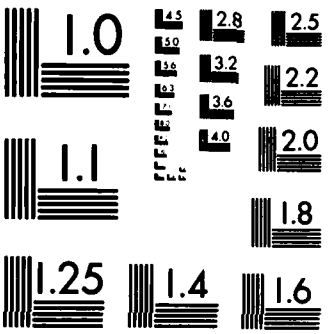

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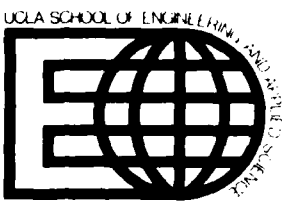

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Attention: David W. Fox, Director
Mathematical and Information Sciences

For:
AFOSR Grant 82-0304

Principal Investigator:
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PERFORMANCE EVALUATION AND CONTROL OF DISTRIBUTED COMPUTER COMMUNICATION NETWORKS

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During the 1982-1985 performance-period under this AFOSR Grant, we have carried out research investigations and obtained many significant results, of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated. In particular, results have been obtained in the following areas: priority-based TDMA schemes; dynamic random-access procedures with applications to local area networks, metropolitan-area network and packet-radio networks; hybrid multiple-access schemes; polling, adaptive poll-

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For:
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Principal Investigator:
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Professor
Electrical Engineering Department

Co-Principal Investigator:
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ABSTRACT

During the 1982-1985 performance-period under this AFOSR Grant, we have carried out research investigations and obtained many significant results, of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated. In particular, results have been obtained in the following areas: priority-based TDMA schemes; dynamic random-access procedures, with applications to local area networks, metropolitan-area networks and packet-radio networks; hybrid multiple-access schemes; polling, adaptive polling and probing access-control techniques; buffer capacity constrained multi-access systems; network topological analysis; polling networks under unbalanced traffic conditions; performance of token-ring and token-bus local area networks; terminal-priority based contentionless access-control algorithms; queueing and telecommunication systems subject to traffic activity mode changes; local area network architectures and protocols for the integration of data/voice/video; integrated packet and circuit switched networks; integrated routing and flow control algorithms in computer networks; performance boundaries for prioritized multiplexing systems.

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I. INTRODUCTION AND SUMMARY

During the 1982-1985 performance period under this AFOSR Grant, we have carried out research investigations and obtained many significant results, of both theoretical and practical importance. A large multitude of computer communication network architectures, models and control schemes have been developed, analyzed and evaluated.

Results have been obtained in the following areas:

1. Performance Analysis for Priority-Based TDMA Schemes for Multi-Access Communication Networks.
2. Performance Evaluation and Control of Dynamic Random-Access and Hybrid Multiple-Access Schemes.
3. Performance Analysis of Polling, Adaptive-Polling and Probing/Reservation Schemes.
4. Performance Analysis and Control of Buffer-Capacity Constrained Multi-Access Systems.
5. Topological Analysis and Design of Survivable Communication Networks.
6. Polling Networks under Unbalanced Traffic Conditions, and the Performance of Token-Ring and Token-Bus Local Area Networks.
7. Priority-Based Contentionless Access-Control Architectures.
8. Queueing and Telecommunication Systems Subject to Traffic Activity Mode Changes.
9. Local Area Network Architectures and Protocols for the Integration of Data/Voice/Video.
10. The Analysis and Design of Hybrid Packet and Circuit Switched Networks.

11. Integration of Routing and Flow Control Algorithms in Computer Networks.

These research studies have been carried out by the Principal Investigators, Professors Izhak Rubin and Mario Gerla, with the participation of a number of Ph.D students, including: L. Clare, L.A. De Moraes, J. Baker, M. Zukerman, S. Katz, P. Rodriguez, R. Pazos, S. Resheff, Z. Tsai, Z. Zhang, L. Jong, V. Minh. Other participants are the following visiting researchers: Dr. Luis F. De Moraes and Dr. J. Hartman, working jointly with Professor I. Rubin; and Dr. Boisson, working jointly with Professor M. Gerla.

Results of the investigations have been presented in Conferences, and submitted for publication in the top journals in the field, as indicated in the Publications section. Many of the underlying research topics are currently being further developed and investigated by us.

II. DESCRIPTION OF RESEARCH INVESTIGATIONS

1. Performance Analysis for Priority-Based TDMA Schemes for Multi-Access Communication Networks

Multiple-access communications channels are used to provide network communications in most utilized distributed computer communication networks. A multi-access channel is shared among a number of, many times diverse, data sources and sinks. The channel access-control (multiple-access) scheme provides for the coordination, supervision and control of the joint sharing of the multiple-access communications channel. The access-control scheme needs to be designed such that it efficiently allocates the limited communications channel resources (time, bandwidth, space and power) under prescribed grade-of-service constraints. Typically, the performance of the multiple-access control procedure is measured in terms of the ensuing delay-throughput performance function. The latter describes the behavior of the message-delay as a function of the channel (or network) throughput. Message delay measures are amended or replaced by blocking probability indices when buffer capacity limitation and/or non-queued assignment disciplines are invoked (as described in Area 4).

Among the key access-control disciplines employed to control the sharing of a multiple-access channel are the Fixed-Assignment TDMA (Time-Division-Multiple-Access) and FDMA (Frequency-Division-Multiple-Access) schemes. Under a TDMA scheme, each network station is allocated periodic time slots during which it can transmit its ready messages. When transmitting, the station occupies the whole channel bandwidth. TDMA schemes allow considerable flexibility in providing multiple-access communications to diverse information sources, and are thus widely used.

Under an FDMA scheme, each network station is allocated a dedicated frequency band. Limited to this band, a station can continuously transmit its ready messages. FDMA schemes have been inexpensively implemented and are therefore also widely used.

TDMA and FDMA schemes are especially efficient in supporting stations which generate steady traffic streams. Other multiple-access schemes are employed to support stations which generate traffic in a bursty, low duty-cycle fasion. Random-access and Polling schemes provide such efficient control for lower network throughput levels, as noted in Areas 2 and 3. At medium to high traffic levels, reservation schemes (and Polling procedures, when the Walk Time is short, see Area 3) provide efficient coordination of the multi-access network.

Under a Reservation scheme, ready stations transmit first a reservation packet which designates their needs for channel transmission service. Transmission slots across the channel are then allocated according to these requests, on a first-come first-served (FCFS) or priority basis. The allocation can be performed in a centralized or fully distributed fasion.

Our research investigations, supported by this Grant over the period starting at 6/30/82, have already yielded important results in this area. In particular, the following priority model has been applied. Messages are categorized as belonging to one of two priority classes. (Extensions to more than two priority classes would then be carried out, directly based on the above results.) Priority-1 messages are designated higher priority than Priority-2 messages. Two basic priority service disciplines are assumed:

1. Non-preemptive: Priority-1 messages are served prior to priority-2 messages, but an ongoing priority-2 message transmission cannot be interrupted.
2. Preemptive-resume: Priority-1 messages are served prior to priority-2 messages; if a priority-1 message arrives during the transmission of a priority-2 message, it waits until the current message sub-block (called packet) ends its transmission, and it subsequently interrupts the priority-2 transmission; the latter message transmission later resumes with the transmission of the subsequent message blocks, so that channel capacity is not wasted.

The above priority-based multiple-access systems are modeled as priority discrete-time queueing systems with proper message batch streams and multiple-packet message (service) lengths. The arrival streams of each priority class are assumed to be general independent stochastic point processes, of which Poisson processes constitute a special case. We have derived message delay steady-state distributions for these schemes. For these systems, no message delay results currently exist in the queueing literature or in the computer communications research literature. Further note that the special structure of a TDMA system induces a specially time-interrupted service (transmission) process. We have also obtained queue-size distributions, describing the statistical fluctuations of the station buffer packet occupancy process. As derived by us previously for non-priority systems, we have further derived statistical characterizations of the delay difference between priority-based FDMA and TDMA schemes.

The results we have derived under such a discrete-time priority

TDMA model, based on investigations supported by this Grant, are presented in [1].

We have also obtained results, based on studies performed under this Grant, for message delay distributions for a TDMA scheme, under a Non-Preemptive continuous-time based priority discipline [2]-[3]. Under this model, the arrival and message-length processes are discrete-time, as assumed in [1]. However, while messages arriving within the same frame, and belonging to the same priority class, are served at random order under the model in [1], we assume a first-come first-served discipline for such messages in [2]-[3]. We have developed a simple but powerful analytical technique, which was used to derive the moment-generating-function of the message delay distribution. The latter function has been used then to derive message delay moments.

We have derived important results for TDMA systems under limited buffer capacity conditions in [4]-[6], [15]. In these studies, we have derived analytical procedures that provide for queue-size and message delay calculations for TDMA schemes, under prescribed buffer capacity limitations. These results are of significant importance in carrying out performance analysis for many practical multiplexing and multiple-access multi-user communication channels, with critical buffer capacity limitations. This work is still ongoing.

Using Markov-Renewal stochastic process models, we have also derived the distribution of the queue-size and message delay functions over the TDMA frame. (See [4]-[6], [15].)

2. Performance Evaluation and Control of Dynamic Random-Access and Hybrid Multiple-Access Schemes

Random-access schemes provide a simple mechanism for efficiently sharing a multiple-access communications channel among bursty, low duty-cycle, terminals. Interactive computer terminals and packet-oriented information sources (such as those which dominate packet communications in military networks) serve as examples of widely-used terminals which generate bursty traffic streams. Under a random-access scheme, a ready packet is transmitted across the channel at proper time, as determined by the access-control scheme, with no or minimal coordination among the transmitting terminals. As a result, at certain times messages may collide (by being transmitted at the same time) and consequently destroyed. Colliding messages are then retransmitted after a random delay, as determined by the governing access-control algorithm.

A number of random-access procedures have been proposed, investigated and implemented. Previously, I. Rubin introduced the Group-Random-Access (GRA) scheme. Under this scheme, a group of the network stations which wish to share the multiple-access channel on a random-access basis, is allowed to transmit their ready packets within designated periodically recurring time-periods. Colliding packets are retransmitted in a subsequent time-period, at a randomly chosen slot.

The GRA procedure entails a number of significant advantages:

1. It is simple to implement.
2. It readily permits the implementation of a hybrid access-control procedure, under which different network groups employ different access-control algorithms, to match their own traffic statistics and grade-of-service needs.

3. It allows the implementation of a multi-priority station group hierarchy.

4. The scheme incorporates a simple control mechanism, which makes it stable.

We have extended the structure of GRA schemes to allow dynamic adaptation in the procedural structure. The scheme would then adapt its time-period structure to correspond to the underlying channel traffic, as observed by the network users through their recordings of the numbers of collisions and successful transmissions within each period. In addition, Channel-Sense GRA schemes have been developed and analyzed. The resulting dynamic schemes yield substantial performance improvements.

We have developed in [7]-[8] such an adaptive random-access procedure, called Dynamic-Group-Random-Access (DGRA) scheme. We have also carried out preliminary throughput and message-delay performance analysis studies for the DGRA schemes. Synchronous as well as asynchronous channel-sense structures have been incorporated. We have shown such schemes to yield excellent delay-throughput performance characteristics for local-area and local-distribution networks, under various channel/equipment/system conditions. In particular, channel-sense asynchronous DGRA schemes have been shown to exhibit superior performance as access-control schemes for half-duplex broadcast local distribution systems, such as those involved in miltary packet-radio and mobile data radio communication networks.

We have also continued out investigations of Hybrid access-control policies. Hybrid schemes need to be implemented in many military and

commercial networks to allow acceptable grade-of-service levels and efficient channel bandwidth sharing, when:

1. The network stations are of heterogeneous nature, being characterized by distinct statistical traffic processes and grade-of-service requirements.
2. The underlying network traffic characteristics statistically fluctuate with time, so that certain access-control algorithms are efficient at certain times, while at other times different algorithms must be employed to provide acceptable communications support.

We have recently developed and analyzed in [9]-[10] a hybrid TDMA/Random-Access Multiple-Access (HTRAMA) scheme. This scheme incorporates both TDMA and Random-Access protocols. The structure of the scheme is dynamically adapted to assume the best TDMA/Random-Access proportion so that it yields the best delay-throughput behavior for the underlying estimated network traffic conditions. In this fashion, the scheme provides a stable operation and exhibits good message delay levels over the whole throughput range.

3. Performance Analysis of Polling, Adaptive-Polling and Probing/ Reservation Schemes

Polling schemes are widely used in data communication networks to provide multiple-access and multiplexing control. Under a polling procedure, a central station (nominated as the central controller) queries in-turn the network stations. Upon receiving a query message, a station either transmits its ready message, or responds with a "no-message" reply. Thereafter, the next network station is queried.

A number of performance analysis papers for polling schemes have been published. However, these papers derive only results for the queue-size distribution, and obtain subsequently an estimate of the message waiting time (in the form of a "virtual waiting-time").

Pure polling schemes induce long message delays when long "walking-times" (time required to propagate the transmit query and response packets) are experienced, and when low duty-cycle terminals need to be supported, under low or medium throughput levels. Better channel utilization and grade-of-service levels are then attained when probing/reservation polling schemes are used. Such schemes used proper probing of sets of network stations to provide access to the underlying multi-access channel. In a distributed control environment, the probing procedure is replaced by a reservation process.

We have developed techniques to analyze such a probing/reservation scheme which uses a Tree-Random-Access algorithm to provide access to status (reservation) messages transmitted by the active network stations. Such a control algorithm, which can be implemented in a centralized or distributed fashion, is shown to be easily implementable and to yield good message delay and throughput performance characteristics. Under

this Grant, we have further developed and analyzed such Polling, and Probing/Reservation schemes [11]-[12].

We are currently investigating the design and performance of integrated polling/random-access architectures. Under such schemes, primary stations gain access into the channel through a polling procedure. Secondary stations are associated with a primary station, and gain access for transmission across the channel when probed by a primary station.

4. Performance Analysis and Control of Buffer-Capacity Constrained Multi-Access Systems

We have studied multiple-access systems that are buffer capacity constrained. In these systems, due to limitations imposed by the limited capacity of the data storage facilities, buffer overflows can occur. It is thus required to evaluate the probability of overflow, or the probability of message blocking (in preventing such overflow).

As noted in Area 1, we have recently derived results for limited buffer capacity multiple-access systems that employ TDMA controls. We have also been developing methodologies to categorize the realizable multi-dimensional regions of blocking probabilities for such systems, when general priority-based control disciplines are employed. These results should be of significant interest to the network designer and analyst, in allowing him to assess what levels of blocking probabilities can be realized, for each priority message class, and what the characteristics are of policies to be used for their implementation.

We have recently obtained such initial results, through investigations supported by this Grant, in [13], [36]. We have considered these systems in which many data sources are multiplexed over a single communication channel, through a buffer with limited capacity. We characterize the admissible set of all possible performance vectors, as we span the set of all queueing service disciplines.

5. Topological Analysis and Design of Survivable Communication Networks

It is of key importance for many military and commercial applications, to ensure that a communication network topology attains a high degree of survivability under nodel/line failures. For such an analysis, the network structure is typically represented as a graph, and its invulnerability is expressed in terms of a graph-theoretical connectivity index. Furthermore, it is important to design the network topological structure such that it ensures, at the same time, a high degree of survivability (connectivity), and an acceptable grade-of-service level (such as message delay), under a limited amount of total resources such as total communication network bandwidth. Such models and analysis and design methodologies have been developed by Dr. Rubin in a paper published in IEEE Trans. on Communications, Jan. 1978. In this paper, the network survivability is expressed by the graph connectivity, the message delay measure is related to the graph diameter, and the overall network capacity (bandwidth) level is represented by the number of lines of the graph.

It is of further importance to guarantee that under node or line failures, the network will not only continue to operate, but that it will operate at an acceptable grade-of-service level. For that purpose, using a graph theoretical model, the notion of diameter-stability was defined by Dr. I. Rubin and Dr. J. Hartman in a recent paper. The latter measure ensures that under a certain number of node/line failures, the diameter of the graph (the message delay across the network) will not increase beyong a specified level. Such survivability and diameter-stability measures are of key importance in the analysis and synthesis

of communication network topologies.

During Fall 1982, Dr. I. Rubin and Dr. J. Hartman, supported by this Grant, carried out further investigations in this area. Models have been evaluated for examining various network survivability and diameter stability issues [14]. In addition to the graph models mentioned above, the graph theoretical concept of domination has been considered for application to various aspects of communication network topological survivability.

6. Polling Networks under Unbalanced Traffic Conditions, and the Performance of Token-Ring and Token-Bus Local Area Networks

Of particular practical importance in evaluating the performance behavior of polling networks is the consideration of unbalanced traffic conditions. Such conditions arise in many common situations whereby certain terminals generate higher traffic intensity levels than others. In [16], we have studied the performance of gated and exhaustive polling communication networks under unbalanced traffic conditions. We show that these two categories of net control algorithms exhibit a distinctly different message delay behavior, as a function of traffic distribution conditions. These results are important to the design of local-area, packet-radio and metropolitan-area communication networks.

We employed our polling results to evaluate the delay vs. throughput performance of local area networks operating under token-ring and token-bus architectures. Such networks are currently emerging as common implementable systems. Our analysis demonstrates the performance behavior of each system under balanced and unbalanced network traffic conditions. It also provides for a performance comparison between these two network control architectures (see [17]).

We are currently investigating the design and analysis of polling schemes for networks with heterogeneous sources. To utilize the channel bandwidth efficiently, under message delay constraints, we select the "Order of polling" (as reflected by the structure of the Service Order Table) in an optimal fashion.

7. Priority-Based Contentionless Access-Control Architectures

A multiple-access broadcast communication channel model applies to a large multitude of applications, including cellular digital radio, local distribution systems, metropolitan area networks, packet-radio networks and local area networks. In particular, of interest is the situation where the network terminals are classified into distinct precedence levels. Each terminal is identified by its own priority level. Higher priority terminals require, on the average, faster access across the communication channel than the lower priority ones.

In [18]-[19] we consider a terminal priority contentionless access (TPCA) control algorithm, which operates on a conflict free basis as follows. Terminals sense the channel to determine whether the channel is busy or idle. When the channel is idle, a ready priority-i terminal waits for a period of time which allows any of the i-1 higher priority terminals to access the channel. The priority-i terminal gains access into the channel for its ready message only if the channel is detected idle during the wait time.

Two key system parameters are incorporated in our model. The acquisition delay (Δ) represents the time period elapsed from the instant a terminal initiates its message transmission process to the instant that all other network terminals detect the channel to be busy with this terminal's message transmission. The delay component Δ is determined by various channel characteristics and equipment hardware and software factors, including: propagation delays, turn around times, power build-up times, reception attack times, certain synchronization preamble times and processing times. The second system parameter of

practical significance is the busy-to-idle detection time γ. It represents the time required by a terminal to determine the termination of an ongoing transmission, and thus conclude that the busy channel has become idle. Many digital radio networks (which largely use half-duplex transceivers) are characterized by relatively high Δ and γ levels. Their performance thus critically depends on these parameters, as shown in our analysis.

TPCA-type access control policies have been implemented in various communication nets for a long period of time (e.g., in various military VHF radio nets). However, no analytical performance evaluation procedure has yet been developed for such schemes. In our studies, we present a precise delay-throughput performance analysis for the TPCA system. Analytical results are derived for the moments and transform of the message waiting-time distribution at each network terminal. Performance curves are presented under various system parameter conditions which correspond to applications involving digital radio local distribution systems and metropolitan-area, packet-radio and local-area communication networks.

We currently carry out further investigations in this area ([37]).

8. Queueing and Telecommunication Systems Subject to Traffic Activity Mode Changes

Many real life queueing systems (in communication, transportation, etc.) exhibit random fluctuations in their arrival rate. Queueing systems typically oscillate between periods of heavy and light traffic. However, reviews of the literature indicate that insufficient work has been done in this area. Frequently, the arrival rate is assumed to be constant over the entire period. In some cases, unfortunately, a design based on this analysis causes the system to overflow. In this study, we analyze queueing the telecommunication systems where the arrival and the service rate are subject to extraneous traffic activity mode changes based on an underlying two-state Markov process. In other words, the system can be in either one of two modes: mode 0 and mode 1, which represent light and heavy traffic, respectively. The models being considered in our recent studies are divided into two classes, according to the time measuring strategy used: continuous and discrete. Preliminary results are in [20]-[21], and in [33]-[35].

Continuous Time Models

The continuous time models discussed in our studies are generalizations of the classical M/M/K and M/M/∞ queueing models. This generalization can be described by the introduction of an extraneous process of modes, denoted by $\{s(t),\ t \geq 0\}$, which can be in one of two modes (0 or 1). When the system is in mode i (i=0,1) the interarrival and service times are exponentially distributed with parameters λ_i and μ_i (i=0,1), respectively. The time interval during which the system functions at

mode i (i=0,1) is exponentially distributed with parameter $c\alpha_i$, where c is a constant.

For the above described models, which are denoted by $M^{(2)}/M^{(2)}/K$ and $M^{(2)}/M^{(2)}/\infty$, we analyze the statistical characteristics of the queue size steady-state behavior, by first obtaining the z-transform, and then the expectation and the variance of the queue size steady-state distribution. The steady-state performance of these two queueing systems is examined as a function of c. Intuitively, the larger c is the more homogeneous the arrival process is, and therefore the queue is less bursty. As a result, in this study we obtain that if the traffic intensity for one mode is greater than one, even if the average traffic intensity is smaller than one, for model $M^{(2)}/M^{(2)}/K$ (the finite number of servers case), the steady-state expectation and variance of the queue size are approaching infinity as c is approaching zero. However, for model $M^{(2)}/M^{(2)}/\infty$ (where we have infinite capacity of service) and for the case where for both mode 1 and mode 0 the traffic intensity is smaller than 1 in model $M^{(2)}/M^{(2)}/\infty$, the effect of c on the performance is not so significant.

The Discrete Time Models

The discrete time models are characterized by the division of the time into fixed length durations, each of size τ seconds, called slots. We assume that all the arrivals that take place within a slot occur at the end of the slot, start of service must coincide with the beginning of a time slot, and that the duration of service is always an integer number of slots. Time slots are set to start at each time $t=n\tau$, n=0,1, 2,... from one general model, denoted by D.M.D. (Discrete time Mode

Dependent).

The arrival process characteristics are again subject to extraneous mode changes. The extraneous process of modes denoted by $\{s_n, n=1,2,...\}$ is defined as a two-state Markov chain, where s_n, n=1,2,... obtains value of i, i=0,1, if the system is at mode i during the n-th slot. This Markov chain is characterized by the transition probabilities α and β, defined as

$$\alpha = \text{Prob}(s_n=1 | s_{n-1}=0)$$

$$\beta = \text{Prob}(s_n=0 | s_{n-1}=1)$$

The number of arrivals at the n-th slot are denoted by N_n. Thus, we consider the arrival process to be a stochastic process $\{N_n, n=1,2,...\}$ which is dependent upon the mode at each slot. In particular, we denote by P_j^m the probability to have j arrivals within a slot in mode m.

The service system is characterized by a single server and unlimited queue size. The service time is mode dependent. When we are in mode m (m=0,1) the service time is geometrically distributed with parameter θ_m $(1 \geq \theta_m > 0)$, i.e., the probability of the service to terminate at a slot being in mode m is θ_m (m=0,1).

The main application of the above described models is in the area of processing, switching, communication and telecommunication systems and networks, with particular application to message/packet/circuit switching computer communication networks, where random fluctuations in the statistical characteristics of the arrival rates are common. For example, by letting $\theta_0=\theta_1=1$ we have the case of single packet messages, that arrive at a station according to the arrival process described above, and are to be transmitted at a rate of one slot per

packet (message). Also, by setting $\theta_0=\theta_1=\theta$ we have a generalization of the previous example to the case of multi-packet messages where each message consists of geometrically distributed (with parameter θ) number of packets. Notice also, that by normalizing the slot size according to the number of stations we can see that the models of Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) can be incorporated.

For the above described models we analyze the statistical characteristics of the queue size and delay time steady-state behavior. Special consideration is given to the effect of the mode parameters (α and β) on the system performance. It is shown that even for the same traffic intensity (ρ), the process can be extremely bursty (expected delay approaches infinity) as α and β approach zero. This is again happening in the case where, for one of the modes, the traffic intensity is greater than 1, even if the overall average traffic intensity is smaller than 1.

We have recently also extended these models to study the performance of communication and queueing systems which adapt their service rates in accordance with the underlying measured queue-sizes. Such systems also operate under fluctuating arrival modes. These results are of significance in the design of demand-assigned multiple-access communication networks. Our results demonstrate that these schemes achieve a marked performance improvement, in comparison with service policies which are non-adaptive, or which try to estimate the underlying arrival mode ([32]). We are currently continuing our works in these areas.

9. Local Area Network Architectures and Protocols for the Integration of Data/Voice/Video

In the area of local integrated networks most of our interests have been directed to bus architectures. We have recognized that the most popular local bus access protocol, Ethernet suffers of various limitations when used for integrated traffic. Most importantly, it performs poorly at the very high bandwidth x lengths products (say > 1Gbpsxkm) that may be required for real time video applications; and it does not guarantee delivery delays within the tolerances often required by real time traffic.

We have therefore investigated several alternatives to the CSMA/CD Ethernet protocol. For the bidirectional bus we have proposed a token based protocol which effectively removes the bandwidth x length limit. This is achieved by forming "trains" to which each station may append a packet after issuing a reservation. Reservations and packet transmissions are governed by the reception of short control packets named tokens issued by the network end stations. The protocol is described in the paper "Tokenet - A Token Based Bus Structured Local Area Network," by A. Marsan and M. Gerla, presented at the Melecon '83 Conference, Athens, May 1983 ([22]).

We also have studied the possibility of implementing the token protocol to unidirectional bus architectures. This study was motivated by the interest in achieving extremely high bus speeds (on the order of the gigabit per second), which are feasible only with optical fibers. Since the optical fiber bus is intrinsically unidirectional when passive taps are used, the only bus architectures that lend themselves to fiber implementation are the unidirectional ones. Among the various architec-

tures that we examined is the two parallel, unidirectional bus configuration. A token circulates alternatively from one bus to the other, enabling stations to transmit in a collision free, round robin mode.

Several protocols supporting the token mode of operations have been developed. Among then we mention U-NET, an "explicit" token protocol, Tokenless Net, an "implicit" token protocol, and Buzz-Net a hybrid random access/virtual token protocol. These protocols are described in the attached references.

References

(1) M. Gerla, P. Rodrigues, E. Yeh "U-NET: A Unidirectional Fiber Bus Network," to be presented at the FOC-LAN Conference, Las Vegas, September 20, 1984.

Abstract

To satisfy the growing demands of local area communication users, new architectures are required which provide very high bandwidth and satisfy real time delay constraints. Fiber optics networks appear to be a good choice for meeting these requirements. This paper describes a fiber optics bus architecture, U-NET, which is based on a token protocol, offers high bandwidth efficiency, guarantees bounded delay, and is highly fault tolerant. U-NET performance compares very favorably with other fiber bus networks.

(2) P. Aguiar Rodrigues, L. Fratta, M. Gerla "Tokenless Protocols for Fiber Optics Local Area Networks," presented at the ICC '84 Conference, Amsterdam, May 1984.

Abstract

A family of distributed bus access protocols is presented. The medium is a pair of unidirectional fiber optics busses to which stations are connected via passive taps. The protocols provide Round-Robin conflict free bounded delay access to all stations. Contrary to most round-robin access schemes, they do not require transmission of special packets (tokens); rather, they simply rely on the detection of bus activity at each station.

(3) M. Gerla, P. Rodrigues and C. Yeh "Buzz-Net: A Hybrid Random Access/ Virtual Token Local Network," presented at the GLOBECOM Conference, San Diego, December 1983.

Abstract

Buzz-net is a local network supported by a pair of unidirectional busses, to which stations are connected via passive interfaces. The access protocol is a hybrid which combines random access and virtual token features. More precisely, the network operates in random access mode at light load and virtual token mode at heavy load. Buzz-net can find applications in fiber optics networks, which are intrinsically unidirectional. This paper describes the protocol and compares its performance to that of other unidirectional bus schemes.

References

(4) M. Gerla, P. Rodrigues, and C. W. Yeh "Token-Based Protocols for High-Speed Optical-Fiber Networks", Journal of Lightware Technology, Vol. LT-3, No. 3, June 1985.

Abstract

The local network medium is a pair of unidirectional fiber-optic busses to which stations are connected via passive taps. For this configuration, we present several protocols which provide round-robin, bounded delay access to all stations, and are particularly suited for high-speed transmission. The common characteristic of the protocols is the use of the token as the synchronizing event to schedule transmission. The token may be explicit (as in U-Net) or implicit (as in Tokenless Net). It may be used all the time, or it may be used simply to resolve collisions (as in Buzz-Net). The protocols are shown to be cost effective at very high (bandwidth) x (length) products that are the unique tharacteristic of high-speed single-mode fiber networks. Furthermore, they are robust to failures because of the passive interfaces and the totally distributed control. The implementation of these protocols on fiber-optic busses is also discussed in the paper.

Reference

(5) P. Rodrigues, L. Fratta, M. Gerla "Tokenless Protocols for Fiber Optic Local Area Networks", to appear in IEEE-SAC, 1985.

Abstract

A family of LAN (Local Area Network) protocols is presented. The LAN consists of a pair of unidirectional fiber optics buses to which stations are connected via passive taps. The protocols provide round-robin bounded delay-access to all stations. Contrary to most round-robin access schemes, the protocols do not require transmission of special packets (tokens); rather, they simply rely on the detection of bus activity at each station. The performance of these protocols in various traffic conditions and system configurations is evaluated via analysis and simulation.

10. The Analysis and Design of Hybrid Packet and Circuit Switched Networks

In the area of hybrid packet and circuit switching systems we have dedicated most of our efforts to the study of express pipe networks. An express pipe is a physical circuit established between an arbitrary source/destination pair in a hybrid network and used to transfer packets transparently (i.e., without need of buffering, reassembly and queueing at intermediate nodes) from source to destination. An express pipe network is a network in which each node pair is connected by one or more express pipes. The main advantages of express piping are the reduction of node delay and node processing overhead due to the fact that packets travel directly from source to destination without being inspected nor queued at intermediate nodes. One drawback of express piping is the reduction in bandwidth sharing flexibility caused by the preallocation of network bandwidth to pipes.

Two problems concerning the design of express pipes have been addressed: (1) Optimal Bandwidth Allocation and (2) Optimal Routing. The first problem consists of finding the best allocation of trunk bandwidth given that the express pipe layout and the distribution of traffic among parallel pipes are known. The objective function is the average packet delay. The constraints are the trunk capacities. The problem can be shown to be convex (i.e., convex objective over a convex constraint set). Therefore, a straightforward steepest descent procedure leads to the global minimum.

The optimal routing problem consists of finding the best distribution of packets over a predefined express pipe network (i.e., pipe layout and bandwidth are given). Again, the objective is the average

packet delay. The problem is shown to be very similar to the optimal routing problem in a packet switched network. The original topology is replaced with a "second order" topology and the Flow Deviation algorithm is applied to the latter to obtain the optimal routing solution.

The results of these investigations have been reported in reference (1) (2) and (3) below.

References

(1) M. Gerla, R. Pazos-Rangel "Bandwidth Allocation and Routing in ISDN's," IEEE Communications Magazine, February 1984.

Abstract

The goal of communications network design is to satisfy user requirements with the minimum amount of investment. This paper presents a method for the optimal design of ISDN's. First, three multiplexing systems that allow the integration of circuit-and-packet switching traffic are described. Then, a key design problem — bandwidth allocation and routing for integrated networks — is formulated, and efficient methods for its solution are presented.

(2) R.A. Pazos-Rangel "Evaluation and Design of Integrated Packet Switching and Circuit Switching Computer Networks," Ph.D. Dissertation, Computer Science Department, UCLA, 1983.

References

(3) R. Pazos, M. Gerla "Express Pipe Network Design", submitted to the International Zurich Seminar on Digital Communications, March 1986.

Abstract

An integrated network can be conceived as composed of a packet switching (PS) subnetwork and a circuit switching (CS) subnetwork. Because of the integrated network flexibility, the PS subnetwork topology can be dynamically changed to match varying traffic demands. As shown in this paper, the packet delay attainable using a flexible PS subnetwork can be as much as 47 % smaller than that of an inflexible PS subnetwork. The purpose of this paper is to study the optimal design of PS subnetworks. For this problem, the mathematical formulation, optimality conditions and an efficient method of solution are presented. Finally, the experimental results obtained from a computer program based on this method are discussed.

11. Integration of Routing and Flow Control Algorithms in Computer Networks

Routing and flow control are two fundamental control procedures in computer networks. Routing is responsible for finding optimal paths and flow control is responsible for preventing congestion by regulating external inputs. It is important to coordinate the two activities so that they reinforce each other (instead of conflicting with each other). For example, at the network entry point, it is useful to know which paths are available in the network, (i.e., routing information) before deciding whether to accept data for a given destination (flow control decision).

Flow control can be exercised by user window adjustment (window control). Routing can be implemented using distributed or centralized algorithms. Finally, the objective of the optimization problem could be delay (to be minimized) or throughput (to be maximized) or some other performance measure which includes both delay and throughput.

In the past year, most of our research has focused on a problem with flow control, centralized routing and minimum delay as the objective function. We have succeeded in showing that a routing solution which minimizes the delay also maximizes the throughput. We have also shown that in the case of a single chain network (i.e., all the traffic has a common source and a common sink) the delay is a convex function of the flows. This results implies that a local minimum is also a global minimum. Thus, any descent technique can be used to find the optimal solution. A very efficient algorithm based on Mean Value Analysis and Flow Derivation was developed to find optimal routing solutions. The algorithm is described in reference [30].

The second problem is the definition of a satisfactory measure of fairness which is minimized (or maximized) when the network resources are fairly shared among all users. This measure of fairness should take into account individual user traffic demands and delay requirements. Since fairness is a function of throughput and delay performance and this in turn depends on routing and flow control, the optimal fairness problem becomes in fact an integrated routing and flow control problem.

Work has focused on the minimization of a fairness measure consisting of the sum of throughput penalties over all users, where the penalty of a user is defined as the difference between desired and obtained throughput, divided by the obtained throughput. An additional constraint in this problem is that the average delay be less than T_{MAX}. An algorithm for finding the optimal routing and throughput allocation has been developed and is reported in reference [31].

More recently, the fairness optimization research was extended to the study of networks subject to window flow control. For such networks, an algorithms for optimal window selection was developed. The algorithm is of considerable practical interest since most current networks use an end-to-end window protocol either at the network level (e.g. X.25) or at the transport level (e.g. TCP). The algorithm is computationally very efficient, in spite of the difficulty of the analysis of the underlying closed network of queues models. The results are reported in reference (2) below.

A survey of fairness schemes so far proposed for packet switched networks is presented in reference (1) below.

References

(1) M. Gerla, H. W. Chan, J. R. Boisson de Marca "Fairness in Computer Networks", ICC Proceedings, Chicago, Ill., June 1985.

Abstract

The success of computer networks is based on the efficient sharing of resources among several users. Network protocols (e.g., routing, flow control, etc.) have been traditionally designed to enhance the sharing of common resources and optimize overall system performance, yet avoiding pitfalls (e.g., congestion, deadlocks, etc.). A key performance criterion in this optimization is fairness, i.e., the ability to provide equal satisfaction to all users, vis-a-vis their demands and the resources available in the network.

In this paper we present a review of several fairness criteria proposed for wide-area, packet-switched computer networks. A taxonomy is proposed and is used to classify and compare the various schemes.

References

(2) M. Gerla, H. W. Chan, "Window Selection in Flow Controlled Networks", 9th Data Comm. Symposium, Vancouver, September 1985.

Abstract

The end-to-end window scheme is a popular mechanism for flow and congestion control in packet switched networks. The window scheme may be implemented in the transport layer protocol (like in TCP), or in the source-to-destination protocol (like X.25). In many implementations, the window size is chosen at connection set up time.

In this paper, we provide guidelines for window selection. Specifically, we

show that if the network becomes overloaded, that is, the offered load exceeds network capacity, then the selection of user windows has a critical impact on individual user throughputs. Thus, user windows should be chosen judiciously, so as to satisfy a well defined "fairness" criterion.

We formulate the optimal window assignment as a mathematical programming problem, and show that the exact solution is computationally impractical because of the combinatorial nature of the problem and the complexity of the underlying multiple chain, closed network of queue model. We then develop a heuristic approach which is computationally very efficient and provides nearly optimal solutions. Numerical results are provided to illustrate and validate the method.

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